

Synchronous Commutation as a Method for Alter- nating - Current — Direct- Current Transformation

By L. O. Grondahl

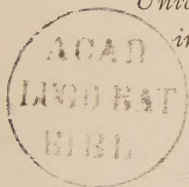
*Abstract from a Dissertation Submitted to the Board of
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in conformity with the requirements for the
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Biography.

LARS OLAI GRONDAHL.

Lars Olai Grondahl was born on a farm near Hendrum, Minn., Nov. 27, 1880. His parents were Peder Elias and Herborg Larson. He received his preparatory education in the district school and at Concordia College, Moorhead, Minn. In the fall of 1899 he entered the preparatory department of St. Olaf College, Northfield, Minn., where he attended steadily until he received the degree of Bachelor of Science in 1904. The following year he taught physics and chemistry in that college. During this year he completed an investigation of the constituents of some dairy products. For this and extra credits made during the previous years he was granted the degree of Master of Science. During the summer of 1903 he studied botany at the University of Chicago. The summer of 1905 was spent in the mining laboratory of the United States Steel Corporation at Hibbing, Minn., making analyses of iron ores. In the fall of 1905 he entered the graduate department of Johns Hopkins University, choosing physics as his principal subject and physical chemistry and mathematics as his subordinates. In January, 1906, he was awarded a university scholarship. During the years 1906-07 and 1907-08 he has been lecture assistant to Prof. Ames. The summers of 1906 and 1907 have been divided between electrical work and work in the laboratory of the Baltimore Copper Smelting & Rolling Company. While in attendance at the university he has taken the lectures given by Professors Ames, Wood, Bliss, Whitehead and Jones, Drs. Hulburt, Cohen, Barnes, Pfund, Anderson and Mr. Jewell.

The Performance of a Synchronous Commutator.*

By J. B. WHITEHEAD AND L. O. GRONDAHL.

THIS paper is an account of a series of experiments on a rectifying device consisting of a synchronously rotating commutator supplied, through collector rings, with alternating e.m.fs. The single-phase arrangement of this type delivers a pulsating e.m.f., commutates poorly and has received only a limited application in certain types of self-excited alternators. If, however, the commutator is suitably connected and is fed with a polyphase system of e.m.fs., the continuous e.m.f. may be made as uniform as desired, and commutation becomes a question of the angle of lead of the brushes, and the constancy of the frequency. The arrangement adopted in the experiments is described in United States patents Nos. 547,683 and 628,358, granted to Henry A. Rowland in 1895. Hutin and Leblanc¹ have also described a similar device, and several other modifications of the principle have been suggested.² Rowland's idea was never embodied in a device, and no account of performance is given by Hutin and Leblanc other than a statement of satisfactory operation.

The so-called "permutator" of Zipernowski and Deri and the "panchahuteur" of Hutin and Leblanc are kindred in principle, but differ essentially from the arrangement mentioned in that they employ a rotating magnetic field to induce the system of polyphase e.m.fs. in a stationary armature with the usual type of distributed winding connected to the commutator. These machines require an elaborate system of compensating coils for damping higher harmonic e.m.fs. which result from the toothed construction of the magnetic circuit. The brushes revolve synchronously and the operation is thus subject to disturbances from variations of frequency. Excellent account is given of the performance of these machines, several of which are in present service.

* Abstract from a dissertation for the degree of Doctor of Philosophy.

¹ *La Lumière Elec.*, Vol. 47, 1893, p. 51.

² Arnold and La Cour, "Wechselstromtechnik," B. IV, p. 817.

THEORY.

If n e.m.fs. of a symmetrical n -phase system of frequency N be connected in series, the resultant e.m.f. is zero at every instant.

$$k = n - 1$$

$$\sum_{k=0} E \sin \left(B - \frac{2k\pi}{n} \right) = 0; B = 2\pi N t \quad (1)$$

It follows that when such a system is connected in series to form a closed circuit no current exists. The maxima of the e.m.fs. between successive pairs of opposite points on this closed circuit will follow each other around the circuit as they do in a two-pole closed-circuit armature winding. Hence, between two opposite points of the circuit there will be developed a single-phase e.m.f. of frequency N . The value of this e.m.f. at any instant is

$$k = \frac{n-2}{2}$$

$$\sum_{k=0} E \sin \left(B - \frac{2k\pi}{n} \right), \text{ where } B = 2\pi N t. \quad (2)$$

If there are n connections from the n junctions of the e.m.fs. the maximum e.m.f. travels from one pair of leads at opposite ends of a diameter, to the next pair and thus rotates with the frequency of the n -phase system. These leads may be taken to an equal number of commutator segments, and brushes which rotate synchronously on such a commutator will collect direct current. The continuous e.m.f. has the value

$$k = \frac{n-2}{2}$$

$$\sum_{k=0} E \sin \left(B - \frac{2k\pi}{n} \right) \quad (3)$$

all values of the sine being considered positive because negative parts of the wave are reversed with reference to the brushes by the method of connection. As B varies from 0 to $2\pi/n$, from $2\pi/n$ to $4\pi/n$, etc., the value of the continuous e.m.f. passes from a minimum to a maximum and back again to a minimum. The smaller the number of phases, the greater the value of $2\pi/n$ and hence the greater the fluctuations. Since there is one maximum for every $2\pi/n$ th part of a cycle, there are as many direct-current maxima per cycle as there are phases. As the number of phases is increased, the difference between the maxima and the minima is decreased and it is possible to ob-

tain direct current as uniform as may be desired by increasing the number of phases. The difference between maximum and minimum when 12 phases are used is about 3.5 per cent; for 24 phases it decreases to less than 1 per cent.

Any number (n) of phases of e.m.f. may be obtained from a quarter-phase system by the proper distribution of coils on two transformer cores. Moreover, all of these may be connected in series, and leads from their junction points may be connected to the segments of a synchronously driven commutator. Commutation may then be accomplished at various loads in identically the same manner as in a direct-current generator—that is, by shifting the brushes forward to such an extent that the short-circuited coil has induced in it the e.m.f. necessary to reverse the current. Commutation at constant load and frequency should be as perfect as it is in the direct-current generator.

The short-circuiting of a coil by the brushes affects the wave-forms of the continuous e.m.f. and of the transformer flux. The e.m.f. is lowered slightly, by the fact that for the period under the brush one coil is short-circuited and those between this coil and the position of commutation at no-load are reversed. The transformer flux is also sharply reduced by the current in the short-circuited turns if the period of short-circuit is too long. These conditions may not be sufficient to have a prohibitive effect on either the primary or the secondary currents; when they are sufficient they can be lessened by increasing the number of phases, because by increasing the number of phases the e.m.f. per phase producing current in the short-circuited coil is also diminished.

The only irregularities that can occur in the wave of flux oscillating in the uniform and independent magnetic circuits of the transformers are those of low value due to hysteresis and those due to short-circuit at commutation. The latter may be diminished by finding the proper length of time for short-circuit and by increasing the number of phases. Such an arrangement if operable would, therefore, avoid the use of the compensating winding of the panchahuteur, and would be simpler and less expensive. These characteristics are possessed by the simpler arrangement of Rowland and that of Hutin and Leblanc. Each of them requires only a small rotating part and low driving power. The only losses are in the transformers and in the two sets of brushes. The regulation and efficiency of such a machine should, therefore, be good.

APPARATUS.

The energy available for the experiments was obtained at 220 volts, two-phase and 60 cycles. The smaller the number

of phases, the greater the voltage between commutation segments and the greater the consequent short-circuit current in the coil under the brush. In a 12-phase system the fluctuations in the continuous voltage are very pronounced, as already indicated, and by adopting 12 phases and 60 cycles it would appear as though very rigorous conditions of performance were imposed. Sixty cycles requires a much shorter period of commutation and either greater speed or a larger commutator with a greater number of segments than does 25 cycles. It was, therefore, decided to transform the available 60-cycle quarter-phase into 12-phase, and investigate the performance of commutation to direct currents.

The apparatus was constructed for the transformation of 5 kw from 200 volts quarter-phase to 110 volts continuous. This arrangement involved two transformers, each of 2.5-kw rating with secondaries suitably interconnected to give a symmetrical 12-phase system of e.m.fs. of proper value. They were of the core type with a wire space 14 in. long on each leg. The cross-section was cruciform and had an area of 10 sq. in. The induction was chosen in the neighborhood of 4000 lines per centimeter. This arrangement gives as a convenient number of primary turns to form the proper ratios 288, with 0.695 volt per turn. In deducing the number of secondary turns necessary it is to be noted that the effective e.m.f. on the brushes is obtained by their following the maximum of the secondary alternating e.m.f. around the closed circuit as in the converter. If in the general expression for the total e.m.f. between any two opposite points in the closed secondary winding:

$$k = \frac{n-2}{2}$$

$$\sum E \sin \left(B - \frac{2k\pi}{n} \right) \quad (4)$$

$$k = 0$$

there be substituted the values of k and n for 12 phases, there is obtained for the instant $t = 0$ $E_{dc} = E \left(\sin \frac{\pi}{6} + \sin \frac{\pi}{3} + \sin \frac{\pi}{2} + \sin \frac{2\pi}{3} + \sin \frac{5\pi}{6} \right) = 3.73 E$. This value is the minimum of E_{dc} and its variation is about 3.5 per cent. Taking the minimum value of the continuous e.m.f. as 110 volts the maximum value of the e.m.f. per phase of the 12-phase secondary system is 29.5 volts. The average value of E_{dc} is $3.82 E$ or about 112.7 volts.

The method of determining the number of turns on each

transformer for the successive phases is well known.³ In the present case the several phases were formed from independent windings. The secondary turns on each transformer for each phase are as follows:

Phase.	Turns on No. 1.	Turns on No. 2.
1	30	0
2	26	15
3	15	26
4	0	30
5	—15	26
6	—26	15
7	—30	0
8	—26	—15
9	—15	—26
10	0	—30
11	15	—26
12	26	—15

The coils containing 26 turns have about 0.1 per cent too many. The negative sign indicates that the coils are connected

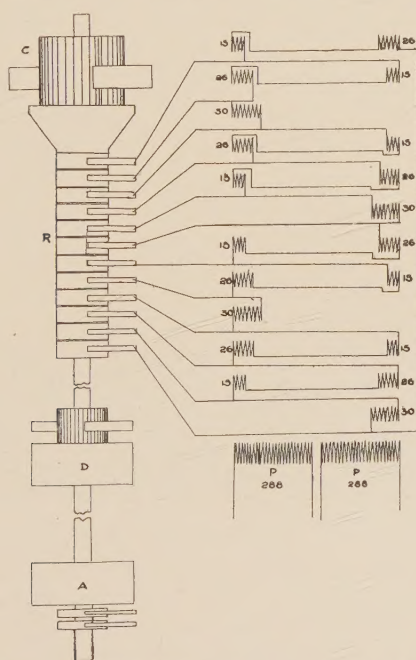


FIG. 1.—INTERCONNECTIONS TO COMMUTATOR.

in the reverse direction. These pairs of coils are connected in series, as indicated in Fig. 1, and between successive pairs 12 leads are taken to an equal number of brushes and collector rings. The coils are so arranged that the two legs on a trans-

³Steinmetz, "Alternating Current Phenomena," Chapter XXXVI.

former always have the same number of ampere-turns similarly arranged, and the primary is wound in two layers on each leg with 72 turns per layer. As calculated, the copper loss per transformer is 2.74 per cent, the iron loss 2.6 per cent, the full-load efficiency 94.7 per cent.

Each collector ring is connected to four equidistant bars in a 48-part commutator. This number of segments for the commutator was chosen so as to reduce the speed to that of an available eight-pole, single-phase synchronous motor. To this motor there was directly coupled a direct-current generator which could also be used as a starting motor. The eight-pole motor makes one-fourth of a revolution for each cycle, which fact necessitates four times as many commutator segments as

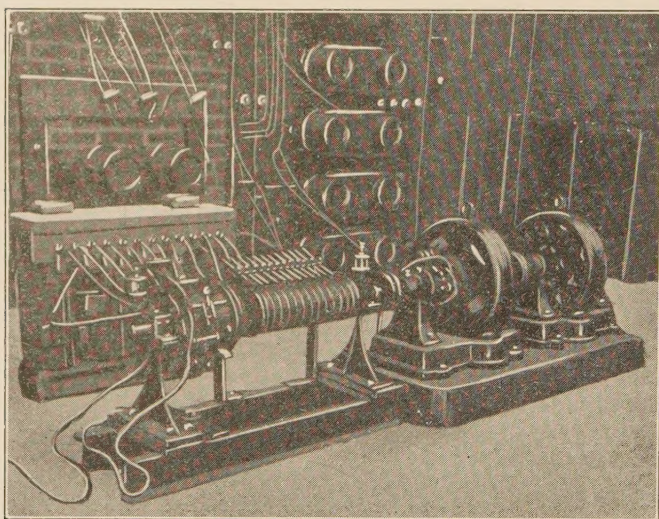


FIG. 2.—GENERAL VIEW OF SYNCHRONOUSLY-DRIVEN COMMUTATOR.

there are phases. The direct current is collected by eight carbon brushes, each $\frac{3}{8}$ in. $\times$ $\frac{7}{8}$ in. in section. The commutator is 6 in. in diameter and has a collecting surface 4 in. wide. With the exception of the commutator the entire construction was carried out in the shops of the Physical Laboratory of the Johns Hopkins University. Fig. 2 shows the general arrangement of the several parts of the apparatus.

PERFORMANCE.

The rotating part is brought up to speed by the direct-current machine used as a motor, and the single-phase motor is then synchronized. When running in synchronism the transformer

primary circuits may be closed and the proper position of commutation may then be found by adjusting the brushes for minimum sparking. On loading the direct-current side, the brush position for sparkless commutation shifts forward. The amount of the brush shift is practically proportional to the amount of direct-current output, and from no-load to full-load is about 4 deg. of arc, or about 0.2 in. on the commutator. A low value for this quantity is objectionable as it renders commutation sensitive to dissymmetries of commutator construction and relative spacing of brushes, and also to oscillations of the rotating part about the position of true synchronism. In the present apparatus the low value is due to the small number of phases. It was also found that the width of six commutation segments taken at various portions of the circumference varied as much as 1/16 in. The frequency variation was sometimes as great as 3 per cent. In spite of these facts, the operation at constant load for any value up to full load was very satisfactory. At 25 per cent overload the sparking would prevent continuous service. In this region the required variation of the brush lead is less than the variations in the symmetry of the apparatus. In the region of one-half load, variations of about one-third full-load are possible with fixed brushes.

REGULATION AND EFFICIENCY.

Data of regulation and efficiency were obtained for the transformers with the rotating part of the machine and also for the transformers alone. The readings are given in Table I.

The change in the continuous e.m.f. from full-load to no-load was from 110.0 to 122.7 volts, 12.7 volts, or 9.7 per cent. In the transformers alone the rise was from 86.5 to 88.5 volts, 2 volts, or 2.26 per cent (Fig. 3). The efficiency of the transformers at full-load was found experimentally to equal 94.0 per cent. The calculated value given above is 94.7 per cent. This must be considered very fair agreement, and indicates that there are no abnormal losses in the magnetic or copper circuits and that the balance of e.m.fs. in the closed secondary circuit is nearly perfect. The loss in the brushes and rotating part increases with the load and varies from 2.5 per cent at 4 amp direct current to 8.0 per cent at 41.2 amp, or full load.

The single-phase secondary e.m.f. given in equation (2) may also be written

$$E_{ac} = \frac{E}{\sin \frac{\pi}{n}} \sin \left(B - \frac{n - 2\pi}{2n} \right)$$

The continuous e.m.f. is given by the same expression if, as before, all values of the sine are considered positive. This

means that the continuous e.m.f. is made up of a series of crests of sine waves. The sine is a maximum for $B - \frac{n-2}{2n} \pi = \frac{\pi}{2}$, or $B = \pi - \frac{\pi}{n}$. For this value of B , $E_{ac} = 3.86 E$. This is then also the maximum value of the continuous e.m.f. The minimum evidently occurs at $B = \pi$ and is $3.73 E$. The average value of a sine wave between $\frac{\pi}{2}$ and $\frac{\pi}{2} + \frac{\pi}{12} = 0.993$ times the maximum value $= 3.83 E$. This is the average value of E_{ac} . The output of the transformers is, therefore, taken as the product of the effective value of the single-

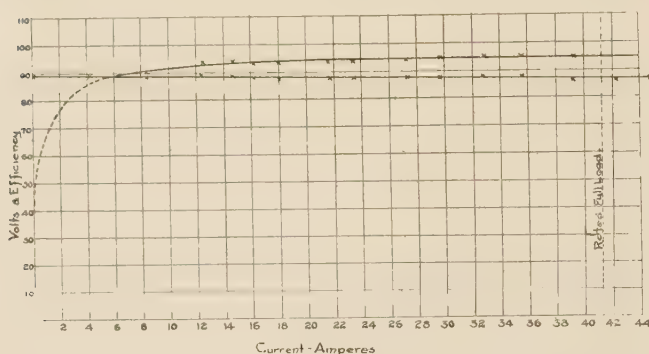


FIG. 3.—REGULATION AND EFFICIENCY OF THE TRANSFORMERS.

phase e.m.f. and the direct current, multiplied by $0.993\sqrt{2}$. This is the value used in Table I, column 9.

TABLE I.

Input.			Output.			Eff.	Volts trans.		Per cent	
Volts.	Amp.	Kw.	Volts.	Amp.	Kw.		Kw.	Eff.	loss in trans.	brushes.
112.6	"	"	125.5	0	0	0	127.3	0	0	0
112.2	1.37	.600	123.8	4.1	.507	84.5	127.2	.522	87.0	2.5
112.0	2.67	1.195	122.0	8.4	1.024	85.9	126.1	1.060	88.8	2.9
111.5	3.78	1.686	120.1	12.43	1.498	88.9	125.7	1.562	92.7	3.8
111.5	4.42	1.971	119.5	14.67	1.752	89.0	125.4	1.840	93.4	4.4
112.2	4.93	2.213	119.0	16.28	1.938	87.6	125.8	2.047	92.3	4.7
110.8	5.44	2.410	117.1	17.98	2.105	87.5	124.1	2.234	92.7	5.2
111.1	6.50	2.886	117.1	21.50	2.517	87.1	124.1	2.670	92.5	5.4
110.1	6.95	3.086	115.2	23.35	2.690	87.2	122.8	2.867	92.9	5.7
110.3	8.10	3.567	114.2	27.22	3.112	87.3	122.3	3.333	93.5	6.2
109.9	8.70	3.821	113.3	29.60	3.355	87.7	122.0	3.612	94.5	6.8
109.6	9.63	4.220	112.6	32.7	3.680	87.3	121.7	3.979	94.4	7.1
109.4	10.53	4.615	110.0	35.7	3.961	86.1	121.6	4.340	94.2	7.9
109.2	11.63	5.070	110.5	39.3	4.340	85.7	120.7	4.740	93.6	7.9
109.2	12.80	5.590	109.7	42.3	4.640	83.0	120.2	5.085	91.1	8.3

The first column of Table I gives one-half the value of the primary voltage. The second column gives the current in one phase of the primary. The input given in column 3 is then de-

terminated as four times the product of this current and the voltage given in column 1. To test the accuracy of this method the input was measured also by means of a wattmeter that had previously been calibrated in terms of the other instruments. The results agreed to within the limit of experimental error—for example, volt-amperes = 0.525 and wattmeter reading = 0.529 kw. The next three columns give voltage, current and the power output on the direct-current side. The total efficiency of transformation given in column 7 is then the ratio of output to input as given in columns 6 and 3. Columns 8 and 9 give the voltage at the transformer secondaries, and their output is obtained as described above. The efficiency of the transformers, given in column 10, is the ratio of the output as obtained to the input. The per cent loss in the brushes and the rotating part was taken as the difference between the total effi-

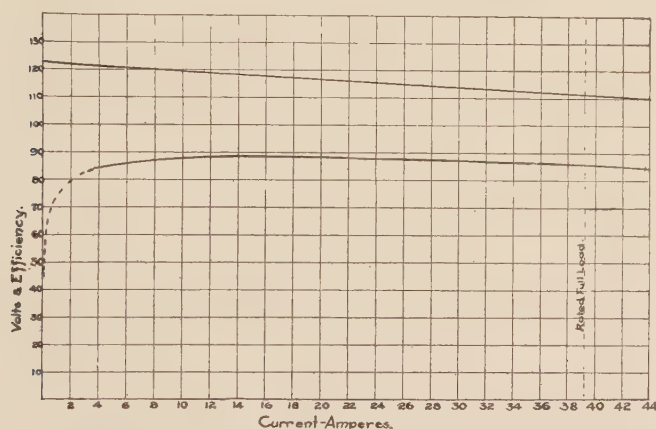


FIG. 4.—REGULATION AND EFFICIENCY PRIMARY OF TRANSFORMERS TO DIRECT-CURRENT BRUSHES, DRIVING POWER NOT INCLUDED.

ciency of conversion and that of the transformers. With increasing load the efficiency of the transformers increases, that of the rotating part decreases, and more rapidly, so that a combination of the two forms a curve with a maximum of 89 per cent at 14 amp direct current—one-third load (see Fig. 4).

With driving power included ($0.35 \text{ kw} = 7 \text{ per cent}$), the total efficiency of the apparatus varies from 74 per cent at 0.1 load to 79 per cent at full-load. As indicated below, the loss in the direct-current brushes at full-load is about 6 per cent, more than half of which may be attributed to mechanical imperfections. The power for driving a commutator and collector rings capable of delivering 500 kw at 500 volts should not

exceed 10 kw, or 2 per cent. With apparatus of this larger rating, therefore, and remembering the higher efficiency of the larger transformers, it is probable that efficiency values in the neighborhood of 90 per cent would be obtainable.

The drop in the voltage in the carbon brushes and contact with the commutator was measured for various values of output. The results are given in Table II. At full-load the drop at this point is about 6 per cent. The values of ohms per square inch, given in the last column, are uniformly more than twice as great as those readily obtainable in direct-current generators. The excess is due in large measure to mechanical vibration and other structural imperfections, and the consequent slight chattering of the brushes.

TABLE II.

Voltmeter readings.	Current.	Volt-amperes.	Contact resistance of four brushes in ohms.	Ohms per sq. in.
1.2	4.2	5.1	.286	.220
1.7	8.6	14.6	.196	.151
2.3	12.0	29.0	.183	.141
2.5	16.5	41.2	.152	.117
2.7	24.4	63.5	.111	.085
2.8	28.1	78.6	.100	.076
3.2	31.9	102.0	.100	.076
3.4	34.6	117.6	.098	.075
3.4	37.4	127.1	.091	.070
3.4	41.0	138.6	.083	.064
3.5	43.6	152.3	.078	.060

In the set of curves, Fig. 5, No. 1 is the percentage drop in the voltage in the transformers proper; No. 2 that due to the shift of the brushes, and No. 3 that due to the resistance of the brushes and to the contact resistance between the carbon brushes and the commutator. No. 4 represents the total drop in voltage. The drop due to the brush shift is observed experimentally by placing on the commutator two search brushes, one in the position of commutation at no-load, the other following the carbon brush.

COMMUTATION.

For constant direct-current output the performance is entirely satisfactory. Such an apparatus would receive limited application, however, unless capable of handling varying loads without attention. Owing to the conditions under which the present apparatus was constructed it is certain that the widest possible variation of load with fixed brushes was not reached. Yet within the rated full-load output, variations of one-third full-load with fixed brushes were handled without serious sparking. Shifting the brushes forward brings the short-circuited coil into a position in which it receives a reversal e.m.f. The value of this e.m.f. does not change with the output, however, and it is constant for a given position of the

brushes. The above-mentioned variations of load were made with the brushes shifted ahead of the exact no-load position.

Automatic assistance to commutation may be provided in several obvious ways. A series of experiments was performed to ascertain what is possible in the way of an automatic arrangement either to accomplish the brush shift or to make commutation possible for all values of load, the brushes being fixed in one position. Obviously retarding the rotating part will have the same effect on the relative position of the brushes and commutation as advancing the brushes. This may be accomplished in several different ways. The following methods were tried for effecting commutation at all loads with the brushes in fixed position:

1. Retarding the rotating part.

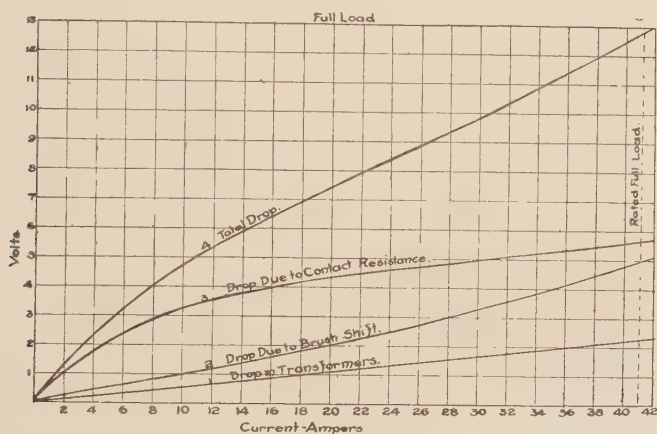


FIG. 5.—DISTRIBUTION OF TOTAL DROP IN ELECTROMOTIVE FORCE.

- (a) By mechanical braking actuated by output current.
- (b) By loading the direct-current generator.
- (c) By variation of the field of the synchronous motor.
- (d) By varying the phase of the e.m.f. applied to the synchronous motor.

(e) By varying the position in space of the resultant motor field.

2. Leaving angular position of rotating part fixed.

- (a) By collecting the direct current by means of split brushes with reactance coils between the halves.
- (b) By inducing an e.m.f. in the n -phase leads by means of commutating poles.

In applying the several methods of retarding the rotating

part no attempt was made to construct the **actuating mechanism** by which the several influences may be made to vary with the amount of direct-current output. Automatic means of applying methods (c), (d) and (e) would offer no difficulty, and the principal aim of the experiments was a determination of the available influence which may be brought into play.

Methods 1 (a) and 1 (b) retard the rotating part by increasing the load on the motor. They thus consume power; they were tried only for the purpose of determining whether automatic commutation is feasible by any method causing the necessary change in the angular relation of the armature and the field pole. Both methods worked admirably, no difficulty being found in adjusting the friction or generator loads for commutation of all loads within the rating of the apparatus.

In method 1 (c) it is suggested to take advantage of the distortion of the weakened field of a synchronous motor by armature reaction, and the consequent angular displacement of the armature. The motor as used was run at its normal impressed e.m.f., but at one-half its normal speed, thus necessitating a highly saturated field. For this reason attempts to apply this method were not found successful. Method 1 (d) was tried as follows:

By inserting in the motor armature circuit a second variable e.m.f. differing in phase by 90 deg., a combination of the two will give any desired change in the phase of the impressed e.m.f. and a consequent change in the angular position of the rotating part. The motor received energy from one phase of the quarter-phase supply system. A transformer, the primary of which was excited from the other phase, had its secondary with a variable number of turns in series with the motor armature. The change in phase was then obtained by varying the number of turns included from the secondary. Any desired change can be obtained. Table III gives one series of readings showing the angular shift resulting from different values of voltage impressed from the second phase. Adjustment for any value of the load was possible by this method. A change from no-load to 30 amp, with the accompanying insertion of voltage, resulted in considerable hunting and sparking, lasting, however, for only a few seconds.

The change in angular position of the rotating part may probably be best accomplished through method 1 (e), that is, by means of auxiliary field-poles, excited by the direct-current output. By this means the resultant magnetic field may be made to shift in such a way that for any value of the load the armature will be in the proper place for commutation. This result can readily be obtained by automatically adjusting the

size, scale and position of the auxiliary pole and the number of turns on it. This method was not tried.

Method 2 (a) was tried with several combinations of split brush with resistance and reactance. No improvement over the conditions with solid brushes could be noted; the same brush lead was necessary and an oscillograph record showed that it had no evident effect on the distortion of transformer flux.

As the load increases so does the counter e.m.f. required to reverse the current in the coil that is commutated. If this e.m.f. could be introduced from some external source, the usual brush shift would not be necessary. This result may be accomplished by means of commutating poles. A pair of such poles excited by the direct-current output were rotated synchronously in proper relation to a series of coils, one in each

TABLE III.

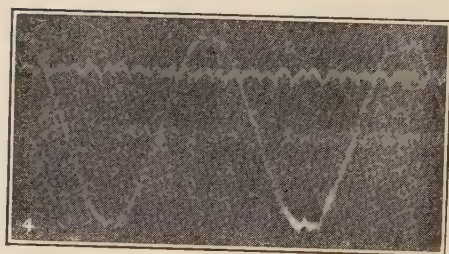
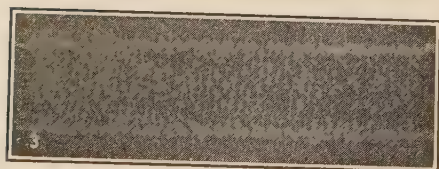
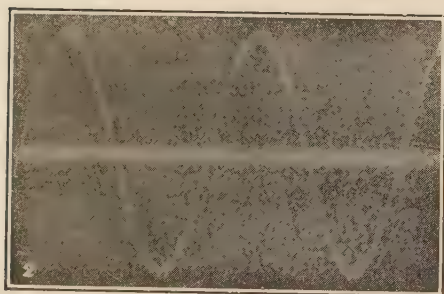
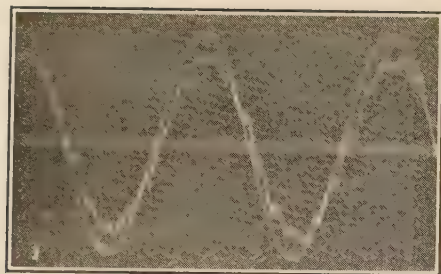
Voltage.	Shift, degree.	Direct-current load.
0	0	0
.5	.4	4.5
1.2	.7	7.5
2.6	.8	8.5
3.7	1.1	11.5
4.6	1.0	11.0
5.7	1.1	11.5
6.6	1.4	14.5
8.8	1.6	16.5
10.7	1.7	17.5
12.6	1.9	19.7
14.4	2.1	21.5
16.6	2.3	23.5
18.8	2.3	23.5
20.9	2.4	24.7
23.0	2.4	24.7
24.9	3.0	30.7

of the 12 phases. Several modifications were tried without any promising results. The limitations of space on the revolving element prevented a thorough investigation of this method, which is apparently a possible one.

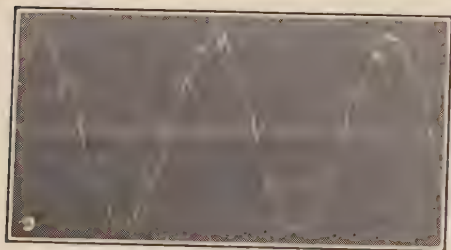
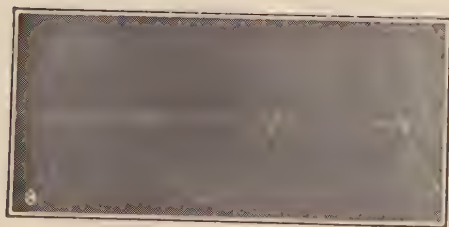
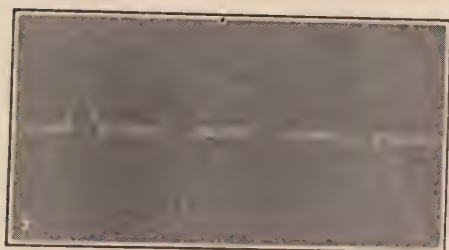
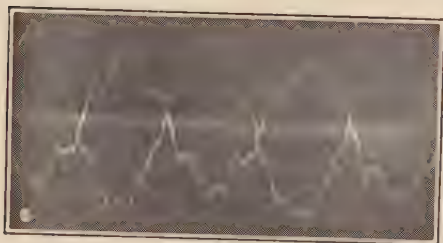
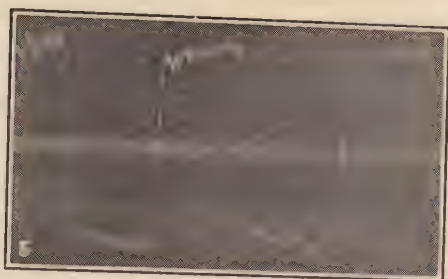
WAVE FORMS.

With a view to obtaining a more intimate knowledge of the performance and to studying the influence of the number of phases on commutation, a number of oscillographs of the various alternating-current and direct-current quantities were taken. Some of these are shown in the accompanying figures:

No. 1, transformer primary impressed e.m.f. and current at full-load; No. 2, alternating e.m.f. between two opposite points of the closed circuit of the 12 secondary phases, at no-load; No. 3, continuous e.m.f. at no-load; No. 4, continuous e.m.f. and resultant secondary e.m.f. at opposite points of closed circuit, full-load; No. 5, current in closed transformer secondary



FIGS. 6 TO 9.—OSCILLOGRAPHS.



FIGS. 10 TO 14.—OSCILLOGRAPHS.

circuit at full load; No. 6, transformer primary current and primary counter e.m.f. at full load; No. 7, current in one collector ring; No. 8, primary counter e.m.f. at no-load; No. 9, primary counter e.m.f. full-load.

The irregularities of the curve of primary current, as shown in oscillograms Nos. 1 and 6—the smoother curve—are seen to be the same as the number of phases in the secondary system. They are caused primarily by the succession of sharp changes in the number of secondary amp-turns. The secondary current has an approximately constant positive and negative value equal to one-half the continuous current. The number of secondary turns on each transformer, however, passes through a cycle of values during each alternating cycle, as may be understood from Fig. 1. Superimposed on this effect are those due to the period of short-circuit of a phase-winding by the direct-current brushes, and to the shifting forward of the brushes.

The effects of short-circuit by the brushes on the resultant alternating secondary e.m.f. may be seen in oscillogram No. 4.

The effect of the fluctuating continuous current on the transformer secondary current is seen in oscillogram No. 5.

The primary counter e.m.f. at no-load should be a smooth curve. The oscillogram for this counter e.m.f. as taken from a test coil on one core is shown as No. 8. The small kinks in this curve indicate the unsymmetrical spacing of the commutator segments. The contact between the brush and the segment does not occur at a uniform time-displacement throughout the cycle.

The primary counter e.m.f. at full-load is badly distorted; the principal cause is the fact that when the brushes are shifted forward a portion of the secondary turns are carrying a reversed current, thereby causing a sharp change in the value of the magnetic induction. In addition, there are the effects of the irregular resultant of secondary and primary amp-turns, and of short-circuit in the coil under the brush. The magnetizing component of the primary current is, therefore, also distorted. The effect on the total primary current is not great, however—see oscillogram No. 6—since the power component corresponding to the secondary output greatly exceeds the magnetizing component.

CONCLUSIONS.

The performance of the experimental apparatus indicates that the commercial possibilities of the principle are greater than have generally been supposed. The distortion of the primary current with as few as 12 phases is not prohibitive. The current distortion and conditions of commutation would be further improved at lower frequency by the use of a greater

number of phases in the secondary system. The rotating element should have a small amount of inertia so as to follow quickly all possible changes of frequency. Commutation is satisfactory at constant load. Automatic adjustment of the conditions of commutation is possible, although sharp changes of load or frequency will be accompanied by more or less serious sparking of short duration. With increasing number of phases the cost and weight would be lessened and the performance would be improved by keeping the commutator fixed and rotating the brushes.



